Influence of birefringence dispersion on spatial resolution of a distributed stress sensor using birefringence optical fiber

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ABSTRACT

Distributed stress sensor with a scanning Michelson white light interferometer can be used to detect stress distribution and its value by analyzing polarization mode coupling caused by stress field in PMFs (polarization maintaining fibers). In the measurement of polarization coupling, the birefringence in sensing fiber is usually considered to be wavelength-independent. The spatial resolution of the distributed stress sensor is invariable, when the optical source spectrum is given. In practical measurement, however, the birefringence in PMF is related with optical wavelength, the birefringence dispersion exists in PMF. Due to the birefringence dispersion, the spatial resolution of the distributed stress sensor descends obviously with the fiber length increasing. In this paper, the influence of external force position and optical source spectrum on spatial resolution in the distributed stress sensor is analyzed, while the birefringence dispersion is considered.

Key Words: Distributed stress sensor, Polarization coupling, Birefringence dispersion, Spatial resolution

1. INTRODUCTION

Over the past few years, optical fiber sensors have been applied widely and played important roles in stress detections[1,2,3]. Such sensors have the advantages over conventional techniques, including immunity to electromagnetic interference, remote sensing, ease of handling, low cost and small size[4,5]. The orientation of birefringence in polarization maintaining fibers can be changed by external transverse forces, which leads to the phenomenon of polarization coupling[6,7]. Accordingly, a distributed stress sensor employing high birefringence polarization maintaining fiber is designed for detecting stress distribution based on measurement of the polarization coupling mode. In the measurement of polarization coupling using white light interferometry, the birefringence in PMFs is usually considered to be wavelength independent, and the difference between the two orthogonal eigenmodes of PMF is invariable[8,9]. The spatial resolution of the distributed stress sensor does not vary with the diversification of the force positions. Whereas in practical measurement, the birefringence is relative with optical wavelength, the chromatic dispersion coefficients are different in two orthogonal axes. Therefore, birefringence dispersion exists in PMFs[10,11,12]. The negative influences of birefringence dispersion on the distributed sensing system become non-neglectable with the increasing of sensing fiber length. The spatial resolution of the system descends obviously along the sensing polarization maintaining fiber due to the

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birefringence dispersion. Meanwhile, the usual relationships between spatial resolution and optical spectrum together with force positions have to be modified on account of the birefringence dispersion in PMFs.

2. WORKING PRINCIPLE OF THE STRESS SENSING SYSTEM

The working principle of white light distributed sensing system is shown in Fig.1. Polarized broadband light is coupled into the PMFs under test with only one polarization mode excited. Ideally the optical wave will remain in the excited mode along all the fiber length. However, when there is an extern force inflicted on the sensing fiber, a little fraction of light is coupled into the unexcited mode, and this causes polarization coupling. Because of the modal birefringence $\Delta n_b(\lambda)$ of the fiber, two polarization modes propagate through the fiber with different group velocities. At the output end of the fiber, an optical path difference (OPD) $\Delta n_b(\lambda)\times l$ is produces between two orthogonally polarized modes, where l is the fiber length between the extern force point and the output end of the fiber. So l represents the extern-force position. Using an analyzer, the two modes are projected to the same polarization direction. The OPD $\Delta n_b(\lambda)\times l$ is compensated by a scanning Michelson interferometer and white light interferograms are read out during the scanning process.

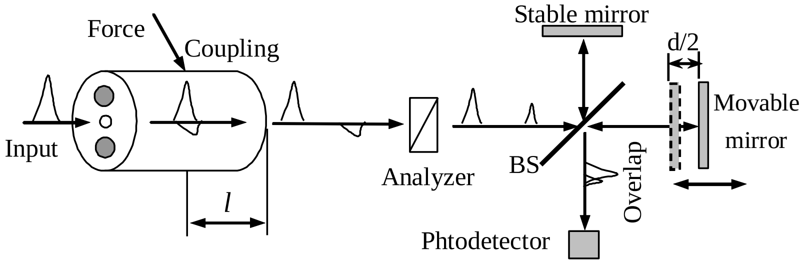


Fig.1. Schematic of the white light interferometer for distributed stress sensing

For stress-induced birefringent PMFs such as PANDA fiber, it is usually considered that their modal birefringence is wavelength independent and $\Delta n_b = \Delta n_b(\lambda_0)$, where λ_0 is the central wavelength of the broadband light. So the OPD generated in sensing PMF is nondispersive and the interference is not affected by dispersion. When there is only one extern-force inflicted on the sensing fiber, the read out interferogram is expressed as:

$$I(d) = I_0\{1 + |\gamma_0(d)|\cos(k_0 d) + \sqrt{h}|\gamma_0(\Delta n_b l - d)|\cos[k_0(\Delta n_b l - d)]\} \tag{1}$$

Where I_0 is the DC component of the interference, $|\gamma_0(x)|$ is the absolute value of optical coherence function of the light source, d is the OPD of the scanning Michelson interferometer, $k_0 = 2\pi/\lambda_0$ is the wave-number in free space, and h is the power coupling strength which indicates the extern force power.

Considering the spectrum of the white light source presents a Gaussian distribution:

$$S(\omega) = \frac{1}{\sqrt{2\pi}\Delta\omega}\exp\left[-\frac{(\omega-\omega_0)^2}{2\Delta\omega^2}\right] \tag{2}$$

Where ω_0 is the center angular frequency, $\Delta\omega$ is the 3dB width of the spectrum. Thus the optical coherence function can be expressed as:

$$|\gamma_0(x)| = \left| \frac{\int_{-\infty}^{+\infty} S(\omega)\exp\{i[k_0(\omega)x]\}d\omega}{\int_{-\infty}^{+\infty} S(\omega)d\omega} \right| = \exp\left[-\left(\frac{2x}{L_{C0}}\right)^2\right] \quad (3)$$

Usually the OPD is larger than the coherence length L_{c0} of the optical source, and the value of $|\gamma_0(x)|$ decreases to zero quickly. So the Equation (1) displays as three interferential packets modulated by the interferential envelop $|\gamma_0(x)|$, as shown in Fig.2. The central interferential packet corresponds to the first AC item in Equation (1). It is the interference between excited optical waves and has no relationship with the polarization coupling. The other two symmetrical interferential packets correspond to the second AC item. They are the interference between excited and coupling optical waves, when the OPD $\Delta n_b \times l$ is compensated by the scanning Michelson interferometer. Two interferential packets contain the same information of the polarization coupling, including coupling strength h and the extern-force position l.

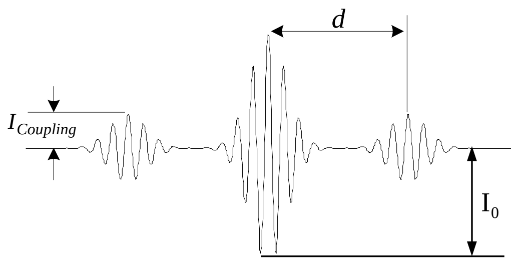


Fig.2. Interferogram with one extern force inflicted on sensing fiber

Considering Equation (1) and Equation (3), envelop of the alternating current item in the interferogram can be expressed as:

$$I_{ac}(d) = I_0 \times \exp\left\{-\left[\frac{2(\Delta n_b l - d)}{L_{C0}}\right]^2\right\} \quad (4)$$

The coupling strength and the position of the extern force can be calculated by analyzing the corresponding interferential packet:

$$h(dB) = 20\log\left(\frac{I_{coupling}}{I_0}\right) \quad (5)$$

$$l = \frac{d}{\Delta n_b} \quad (6)$$

Where I_0 is the DC component of the interference, $I_{coupling}$ is the amplitude of the zero-order fringe in the interference packet, as shown in Fig.2.

The relationship between coupling strength h and the extern force effect can be expressed as following equation:

$$F^2 \sin^2(2\alpha)\sin^2\left[\pi\sqrt{1+F^2+2F\cos(2\alpha)}\cdot\frac{L_f}{L_b}\right]-hF^2-2hF\cos(2\alpha)-h=0 \qquad (7)$$

Where L_b is the beat length of the sensing fiber, L_f is functional length of the extern force, α is the angle between the force and the fiber principal axis, and the extern force $f=\frac{5.4614L_b}{r\lambda}F$ could be calculated from Equation (7) by numerical method, r is the radius of the birefringent fiber..

Spatial resolution is the minimum distance between two adjacent extern-force points which can be distinguished by the sensing system. According to Equation (3) and Equation (5), the spatial resolving distance L_R is a constant decided by the coherence length of the source and the modal birefringence of the polarization maintaining fiber:

$$L_R=\frac{L_{c0}}{\Delta n_b}=\frac{\bar{\lambda}^2}{\Delta\lambda\cdot\Delta n_b} \qquad (8)$$

Where $\Delta\lambda$ is the 3dB band width of the optical source spectrum. For a specific birefringent fiber, its operation wavelength λ and modal birefringence Δn_b is predictable. So the spectrum width $\Delta\lambda$ of the source becomes the only determinant factor for spatial resolution. Wider spectrum means higher spatial resolution. When operation wavelength $\bar{\lambda}=1310.2nm$, $\Delta\lambda=35.8nm$ and birefringence $\Delta n_b=6\times10^{-4}$, the spatial resolution reaches 7.99cm without considering birefringence dispersion in the sensing system.

The scheme of the distributed stress sensing system is shown in Fig.3. It consists of three parts: A superluminescent diode (SLD) as the broadband source, the high birefringent sensing fiber, and distributed polarization coupling measurement module. The principal part of the polarization coupling module is a white light Michelson interferometer with a scanning reflective arm driven by a stepping motor.

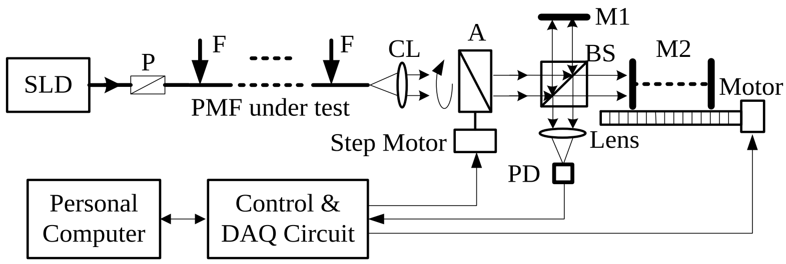


Fig.3. The distributed stress sensing system

3. INFLUENCE OF THE BIREFRINGENCE DISPERSION ON SENSING SYSTEM

In the above description, the birefringence dispersion of PMFs is neglected. As a matter of fact, the propagation constant difference $\Delta\beta(\omega)$ is wavelength dependent, and this leads to the birefringence dispersion existing in PMFs[13,14,15]. The OPD generated in the birefrigent fiber can not compensated for all wavelengths using a nondispersive Michelson interferometer[16,17]. The white light interferograms are distorted. With the length of high birefringent sensing fiber increasing gradually, the influences of birefringence dispersion in PMFs become more and more obvious. Considering birefringence dispersion in the measurement of the distributed stress sensing, the analysis of extern-forces position and spatial resolution need to be modified.

When the OPD of the Michelson interferometer is d, the optical intensity of the interferogram can be expressed as:

$$I(d)=\frac{1}{2}\int S(\omega)\left\{1+\mathrm{Re}\left[\exp\left(i2\left(\frac{\omega}{c}d-\Delta\beta(\omega)\cdot l\right)\right)\right]\right\} \tag{9}$$

According to the definition of the birefringence dispersion ΔD in the high birefringent fibers,

$$\Delta D(\omega_0)=\frac{d\tau_P}{d\lambda}=-\frac{\omega_0^2}{2\pi c}\cdot\frac{d^2\Delta\beta}{d\omega}\bigg|_{\omega=\omega_0} \tag{10}$$

Where τ_P is the average time delay between the two orthogonal polarization modes in PMFs.

Meantime, the propagation constant difference $\Delta\beta(\omega)$ can be expanded in a Taylor series to the second order near the frequency of ω_0:

$$\begin{aligned}\Delta\beta(\omega)&\approx\frac{\omega_0}{c}\Delta n_b+\frac{\omega-\omega_0}{c}\Delta N_b+\frac{1}{2}\frac{(\omega-\omega_0)^2}{\omega_0^2}\cdot\frac{d^2\Delta\beta}{d\omega^2}\bigg|_{\omega=\omega_0}\\&=\frac{\omega_0}{c}\Delta n_b+\frac{\omega-\omega_0}{c}\Delta N_b-\pi c\frac{(\omega-\omega_0)^2}{\omega_0^2}\cdot\Delta D\end{aligned} \tag{11}$$

Where Δn_b is the phase birefringence of the PMFs, ΔN_b is the group birefringence of the PMFs.

Substituting Equation (11) into Equation (9), the optical intensity of the interferogram is given by:

$$I(d)=I_0\times\left\{1+\frac{1}{\sqrt[4]{1+\xi^2}}\exp\left[-\frac{1}{1+\xi^2}\left(\frac{2(\Delta N_b l-d)}{L_{C0}}\right)^2\right]\times\cos\left[k_0(\Delta n_b l-d)-\frac{\xi}{1+\xi^2}\left(\frac{\Delta n_b-d}{L_{C0}}\right)^2\right]\right\} \tag{12}$$

Where I_0 is the DC component, L_{C0} is the optical coherence length of the light source. And ξ is called the birefringence dispersion envelop coefficient, which indicates the accumulation of the chromatic dispersion along the fiber length.

$$\xi=2\pi c\cdot\Delta D(\lambda_0)\cdot l\cdot\left(\frac{\Delta\lambda}{\lambda_0}\right) \tag{13}$$

Here we can know ξ varies with the extern force position l.

According to the description in section 2, the position and power of extern forces can be calculated by analyzing the envelops of the white light interferograms. It is found from Equation (11) that the envelop of alternating current item in the interferogram is expressed as:

$$I_{ac}(d)=I_0\times\frac{1}{\sqrt[4]{1+\xi^2}}\exp\left\{-\frac{1}{1+\xi^2}\left[\frac{2(\Delta N_b l-d)}{L_{C0}}\right]^2\right\} \tag{14}$$

Comparing Equation (14) with the Equation (4), the interferential Gaussian envelop has changed in two aspects: broadening of the envelop width and decreasing of the interference contrast. Assuming that W_2 is the $1/e$ width of the interferential envelop considering birefringence dispersion, it can be calculated from Equation (15):

$$W_2 = \sqrt{1+\xi^2} \cdot L_{C0} \tag{15}$$

The broadening of envelop is a variation increasing with the position of the extern force l, and is given by:

$$\frac{W_2}{W_1} = \sqrt{1+\xi^2} = \sqrt{1+4\pi^2 c^2 \Delta D^2 l^2 \left(\frac{\Delta\lambda}{\lambda_0}\right)^4} \tag{16}$$

Where $W_1 = L_{C0}$ is the $1/e$ width of the white light interferential envelop without the influence of the birefringence dispersion.

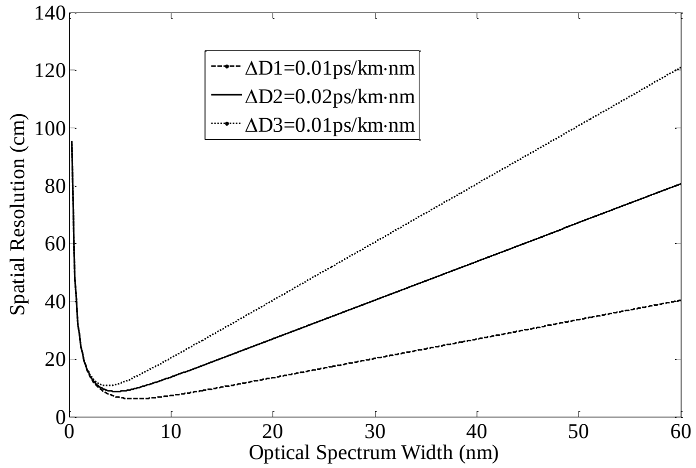


Fig.4. Relationship between the spatial resolution and the spectrum width of light source

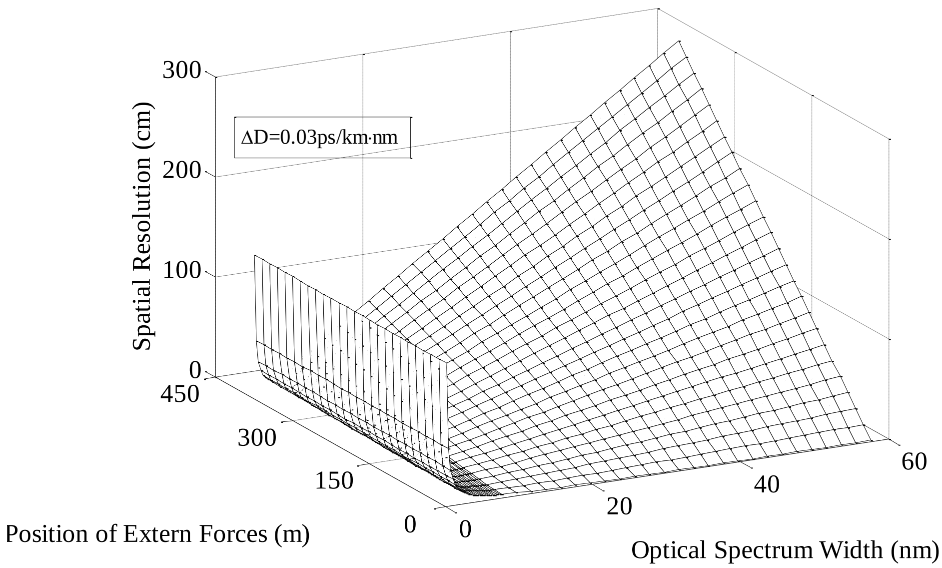


Fig.5. Variation of the spatial resolution with both spectrum width and extern-force position

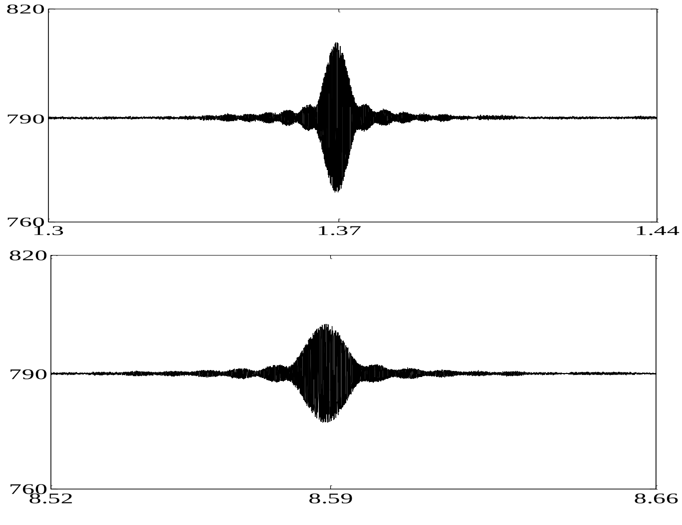
According to the analysis in section 2, in order to distinguish two polarization coupling points, the distance between two extern-force positions needs to exceed over $1/e$ width of the interferential envelop. Hence, the spatial resolving distance L_{RD} of the distributed sensing system can be calculated as follows:

$$L_{RD} = \frac{\sqrt{1+\xi^2} \cdot L_{C0}}{\Delta N_b} = L_b \cdot \sqrt{\left(\frac{\lambda_0}{\Delta\lambda}\right)^2 + \left(2\pi c \cdot \Delta D \cdot l\right)^2 \left(\frac{\Delta\lambda}{\lambda_0}\right)^2} \tag{17}$$

Where L_b is the beat length of the high birefringent sensing fiber, which is constant for a concrete fiber, and l indicates the position of the extern force along the sensing fiber. Equation (18) shows the relationship between spatial resolving distance and spectrum of the optical source obeys a hyperbola distribution, and the spatial resolution decreases with the increasing of the extern-force position. When the optical spectrum meets the condition of $\frac{\lambda_0}{\Delta\lambda} = \sqrt{2\pi c \cdot \Delta D \cdot L}$, the spatial resolving distance reaches its minimum at the position of $l = 100m$ in the sensing fiber, as shown in Fig.4. The variation of the spatial resolution with both spectrum width $\Delta\lambda$ and extern-force position l is shown in Fig.5, when the birefringence dispersion $\Delta D = 0.03\, ps/km \cdot nm$.

4. EXPERIMENTS

The experimental setup of the distributed sensing system can also be illuminated according to Fig.3. A superluminescent diode (SLD) emitting at 1310nm was used as the light source. Its spectrum followed a Gaussian distribution and the 3dB spectral width is approximately 35.8nm. An in-line polarizer is fusion spliced in front of the high birefringent sensing fiber. Its polarization orientation is aligned to the slow axis of the PMF, so that only the slow axis is excited. The output light from the fiber is collimated, passed through a rotatable Glan-polarizer, and then injected into the scanning Michelson interferometer. The interferometer uses a linear translation guide with a range of 300mm, corresponding to the OPD compensating ability for 1km long birefringent fiber. The interference signal is detected with an InGaAs PIN diode and then transmitted into a computer by a programmable data acquisition circuit. The extern forces are pressing on the sensing fiber by an infliction device.



a. Coupling point at 10m

b. Coupling point at 90m

Fig.6. Interferograms of the same coupling point at 10m and 90m

In order to testify the influence of birefringence dispersion, we observed the changes of low coherence interferograms with several fixed coupling points caused by extern forces located at different fiber positions. These are achieved by scanning the same sensing fiber with the same extern force once forward and once backward. For a 100m long sensing fiber, the coupling point produced by extern force at 10m along the sensing fiber could be seen as the coupling point at

90m when we execute the reverse scanning. So the interferograms of the same coupling at different position are obtained, as shown in Fig.6. The phenomenon of interferograms broadening and contrast decreaing are validated obviously in the experimental figure.

Optical filters of 12.55nm and 10.35 are adopted to test the influences of birefringence dispersion at different optical spectrum. Using the uniform method as the above, the $1/e$ width of the interferential envelops at groups of 20m-80m, 30m-70m and 40m-60m are obtained at different spectral width of 35.8nm, 12.55nm, and 10.35nm. The experimental results are exhibited in Table 1.

Table 1. The $1/e$ width of the interferential envelops in different position at different spectrum (The unit is μm)

	10m-90m		20m-80m		30m-70m		40m-60m	
Position	10m	90m	20m	80m	30m	70m	40m	60m
35.8nm	36.725	82.528	34.161	78.847	35.763	71.041	36.829	56.427
12.55nm	109.04	125.35	93.841	103.91	99.502	108.44	110.13	114.85
10.35nm	114.08	132.85	96.406	108.85	104.35	111.36	115.22	119.77

From the experimental results in Table 1, it is found that the tendency of envelop broadening expands with the difference of the extern-force positions and the increasing of the 3dB spectral width. The broadening of interferograms can be estimated using the increasing of the $1/e$ width of the interferential envelop calculated from Equation (15).

Meanwhile, the influence of birefringence dispersion on the spatial resolution in the distributed sensing system stands out in the experiments. The spatial resolution with extern forces inflicted on different positions along the sensing fiber is shown in Fig.7. The spatial resolving distances in the sensing system increase obviously with the position of extern forces, which achieves a good agreement with the Equation (17).

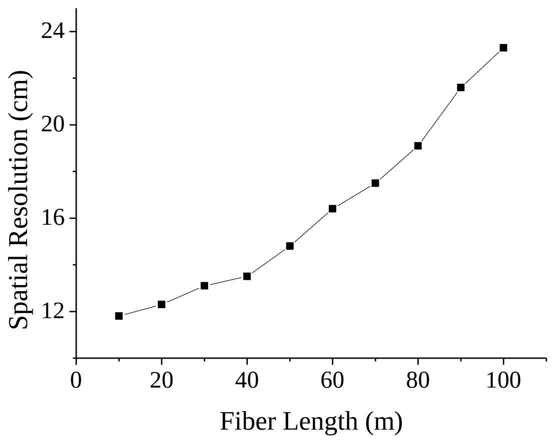


Fig.7. Spatial resolution with extern forces located in different position

Under the condition of different spectral width, the variations of the spatial resolution with the positions of extern forces are also testified, as shown in Fig.8. Firstly, the tendency of the spatial resolution increasing with the extern forces positions is consentaneous under all the spectral width. When the 3dB spectral width is 35.8nm, the influence of the birefringence dispersion is the most distinct, so the tendency of the spatial resolving distance increasing is the most obvious accordingly.

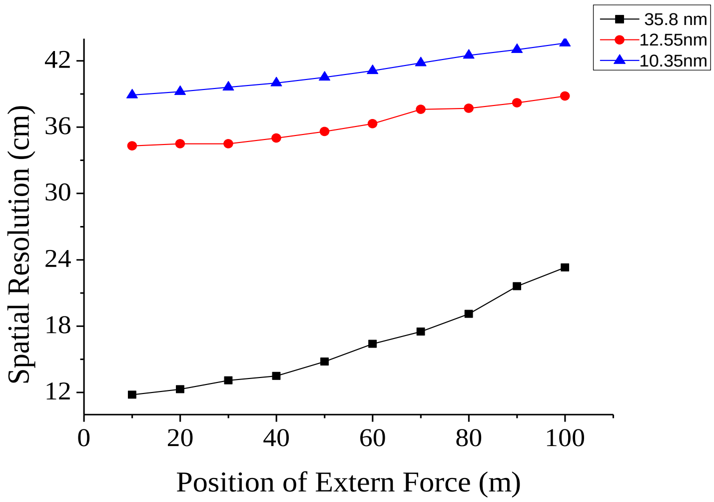


Fig.8. Relationship between spatial resolution and positions of extern forces at different spectral width

5. DISCUSSION IN COMPENSATION OF THE BIREFRINGENCE DISPERSION

In the above sections, it is demonstrated that the influence of birefringence dispersion is critical to the decreasing of the spatial resolution in the distributed sensing system. Due to birefringence dispersion, spatial resolution and other characteristics of the system become awful with the increasing of the position of extern forces. However, the birefringence dispersion is an intrinsic character in the birefringent fibers, of which the infection could only be weakened by minishing the spectral width rather than ultimate elimination. So outside compensation is necessary for reducing the influence. The basic reason lies in the non-dispersive Michelson interferometer, and it can not compensate the OPD generated in sensing fiber at all wavelengths. So a method of inserting a dispersive medium in the immovable arm of the scanning Michelson interferometer is proposed, as shown in Fig.9.

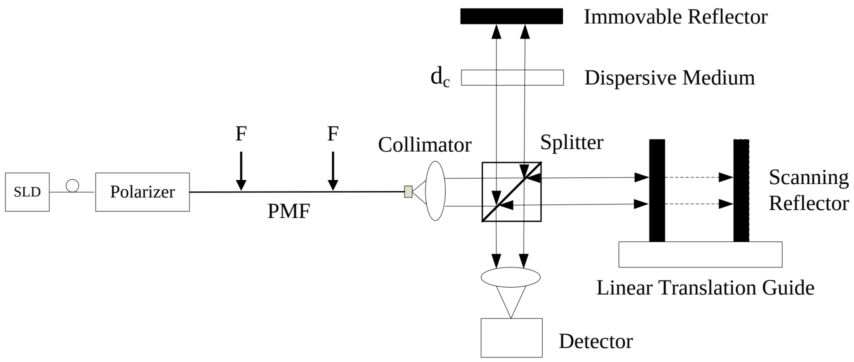


Fig.9. Compensation structure with dispersive medium in Michelson interferometer

According to the description in section 3, after inserting dispersive medium, the optical intensity of the interferogram can be expressed as:

$$I(d) = I_0 \times \left\{ 1 + \frac{1}{\sqrt[4]{1+\zeta^2}} \exp\left[-\frac{1}{1+\zeta^2} \cdot \left(\frac{2(\Delta N_b l - d - 2(n_{C0} - 1)d_C)}{L_{C0}} \right) \right] \right.$$
$$\left. \times \cos\left[k_0 \left(\Delta n_b l - d - 2(n_{C0} - 1)d_C \right) - \frac{\zeta}{1+\zeta^2} \left(\frac{\Delta n_b l - d - 2(n_{C0} - 1)d_C}{L_{C0}} \right)^2 \right] \right\} \tag{18}$$

Where n_{C0} is the refractive index of the dispersive medium at the center wavelength λ_0, d_C is the thickness of the medium. The reflection of birefringence dispersion ζ is calculated as follows:

$$\zeta = 2\pi c \cdot (\Delta D \cdot l - 2D_C \cdot d_C) \cdot \left(\frac{\Delta \lambda}{\lambda} \right)^2 \tag{19}$$

When the dispersive medium is replaced by a dynamic compensation device, the birefringence dispersion in PMFs could be compensated entirely according to Equation (20). In practical measurement, a series of dispersive slices with different dispersion value are applied to equalize the birefringence dispersion in the sensing fibers. If we choose the dispersive medium which can compensate half birefringence dispersion of the fiber appropriately, that is $D_C \cdot d_C = 1/4 \Delta D \cdot l$, the relationship between spatial resolution and the positions of extern forces after compensation is shown in Fig.10.

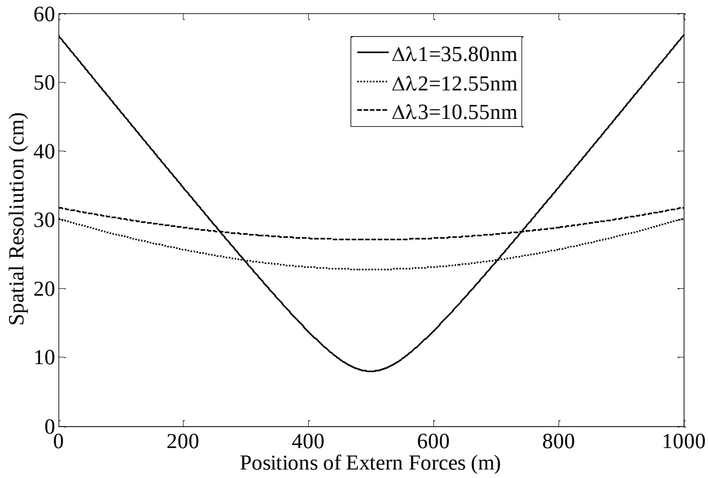


Fig.10. Variation of spatial resolution with extern-force position after compensation of the birefringence dispersion

6. CONCLUSIONS

The influence of birefringence dispersion on the distributed stress sensor is illustrated theoretically and experimentally in this paper. With the increasing of the length of the birefringent sensing fiber, the birefringence dispersion becomes a non-ignorable limiting factor to the spatial resolution of the distributed sensing system. It is found that the spatial resolution decreases obviously with the augment of the extern forces position along the fiber. In the end, a method is proposed to compensate the negative effects of the birefringence dispersion on the distributed stress sensor.

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